

# Hubble Space Telescope Ultraviolet Light Curves Reveal Interesting Properties of CC Sculptoris and RZ Leonis

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## ABSTRACT

Time-tag ultraviolet data obtained on the Hubble Space Telescope in 2013 reveal interesting variability related to the white dwarf spin in the two cataclysmic variables RZ Leo and CC Scl. RZ Leo shows a period at 220 s and its harmonic at 110 s, thus identifying it as a likely Intermediate Polar (IP). The spin signal is not visible in a short single night of ground based data in 2016, but the shorter exposures in that dataset indicate a possible partial eclipse. The much larger UV amplitude of the spin signal in the known IP CC Scl allows the spin of 389 s, previously only seen at outburst, to be visible at quiescence. Spectra created from the peaks and troughs of the spin times indicate a hotter temperature of several thousand degrees during the peak phases, with multiple components contributing to the UV light.

## 1. Introduction

The advantage of spectral data obtained in time-tag mode with the Hubble Space Telescope (HST) is that light curves can be constructed by summing the flux over wavelength. Thus, we were able to search for periodic ultraviolet variability in the observations resulting from a large Cycle 20 *HST* program with the Cosmic Origins Spectrograph (COS) that was designed to obtain the temperature of the white dwarfs in 40 cataclysmic variables (CVs). In CVs with non-magnetic white dwarfs and with short orbital periods (thus low rates of mass transfer), the accretion disk typically contributes 40-75% of the optical light whereas the white dwarf contributes 75-90% of the ultraviolet (UV) light (Szkody et al. 2010). Of the 40 systems in our *HST* program (Pala et al. 2017), two showed periods identifying them as new non-radial pulsators (Mukadam et al. 2017) and

five others had observed eclipses (Pala et al. in prep). Here we report interesting results on the UV variability of two systems that are related to the spin of their white dwarfs: in RZ Leo, we detect for the first time a probable spin period of the white dwarf while CC Scl shows a spin period at quiescence that was previously only evident at outburst.

RZ Leo is a short period (1.825 hr) dwarf nova with a quiescent V mag of 18.8 and 7 past known outbursts (Mennickent & Tappert 2001, Ishioka et al. 2001, Patterson et al. 2003). Its optical spectrum at quiescence (Szkody et al. 2003) shows broad absorption surrounding double-peaked Balmer emission lines, indicative of a high inclination, low mass transfer system. A short cadence (1 min) observation sequence by Kepler K2-1 for 82 days from 2014 May 30 to August 20 (Dai et al. 2016) greatly improved the orbital period determination and showed a 0.5 mag double-humped light variation phased on this period. During the K2 observation, it also showed an unusual brightening event of about 0.6 mag that lasted almost 2 hrs.

CC Scl is a *ROSAT* X-ray source that was identified as a 17.3 mag CV by Schwöpe et al. (2000). Further followup observations revealed spectra with strong Balmer and HeII lines, short duration (9 day) outbursts with superhumps, and an orbital period of 1.40 h (Chen et al. 2001, Ishioka et al. 2001, Woudt et al. 2012). Kato et al. (2015) later used shallow eclipses to determine an inclination of 81 deg, and refine the period to 84.337 min. Using the 2014 superoutburst data, they found a low mass ratio  $q = 0.072 \pm 0.003$ . Longa-Pena et al. (2015) confirmed this low value of  $q$  from spectroscopy and suggested that CC Scl was a post-period bounce system. Observations with *Swift* along with ground-based photometry obtained during an outburst in 2011 (Woudt et al. 2012) revealed a white dwarf spin period of 389.5 s which was only visible during the outburst. The presence of this spin period identified CC Scl as a member of the intermediate polar (IP) group<sup>1</sup>, systems

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<sup>1</sup><http://asd.gsfc.nasa.gov/Koji.Mukai/iphome/catalog/alpha.html>

containing magnetic white dwarf whose spins are not synchronised with their orbits; see Warner (1995) for a review of IPs. Superhumps with a period of 1.443 h were also seen during this outburst, making this system, along with V455 And (Araujo-Betancor et al. 2005a), unambiguous superhumpers containing a magnetic white dwarf.

## 2. Observations

The Cosmic Origins Spectrograph (COS) was used with the G140L grating to obtain time-tag spectra for the two objects in 2013. A general description of the program for temperature determination is given in Pala et al. (2017). The number of *HST* orbits used for each system varied based on their quiescent magnitude. Four *HST* orbits were used for RZ Leo on April 11, and two for CC Scl on June 29. The data were obtained from the archive and spectra were extracted using a 41 pixel width. For period analysis, light curves were created by summing the spectra over a region with good signal (but leaving out strong emission lines) and binning the flux into 5 s bins. The times and spectral regions are summarized in Table 1. The resulting light curves were then divided by the mean and one was subtracted to produce a fractional amplitude. A Discrete Fourier Transform (DFT) period analysis was then accomplished, with the  $3\sigma$  noise level determined by a shuffling technique (see Szkody et al. 2012 for details).

Monitoring of each system through AAVSO alerts and subsequent observations prior to the *HST* scheduled dates determined that each system was at quiescence. Kepler K2 continuous short cadence 1 minute observations on RZ Leo took place in 2014 from May 30 to August 20. The photometric extractions, resulting light curve, and a discussion of the observed double-humped orbital period variations are described in Dai et al. (2016). In this paper, we subjected the short cadence (1 min) dataset to the same period analysis procedure as for our *HST* data.

Further optical photometric observations of RZ leo were accomplished at Apache Point Observatory on 2016 May 29 using the 3.5m telescope with the frame-transfer CCD Agile (Mukadam et al. 2011) and a BG40 broad band filter. Integration times were 15 sec and differential light curves were constructed using comparison stars on the same frames. The light curves were then converted to fractional amplitudes and the DFT computed in the same way as for the *HST* data.

### 3. Results

#### 3.1. RZ Leo

The UV light curve for the four *HST* orbits and the resulting DFT are shown in Figure 1. The double-humped orbital variation at 55 min that has been observed in the optical (Mennickent et al. 1999, Patterson et al. 2003, Dai et al. 2016) is also evident in the UV light curves (the middle of orbit 2 and the beginning and ends of orbits 3 and 4) and in the DFT. The amplitude of this variation is slightly less in the UV (0.3-0.4 in magnitude units) compared to 0.5 mag (Dai et al. 2016) in the optical, although Mennickent et al. (1999) note a large optical variation of the humps during their 11 year study. The model fitting of the UV spectrum by Pala et al. (2017) determined the white dwarf has a temperature of  $15,014 \pm 638$  K and contributes 83% of the UV light. The larger amplitude of the orbital modulation in the optical would be consistent with an origin associated with the accretion disk. While a double-humped orbital variation is fairly common among short orbital period systems, (e.g. WZ Sge), the cause of this variation has been ascribed to several sources. Osaki & Meyer (2002) relate it to a spiral arm structure in the disk when the disk has reached the 2:1 resonance. Skidmore et al. (2002) found that infrared photometry was consistent with changing views of a hot spot during an orbit, while Mennickent et al. (1999) invoked moving hot spots to account for the changes in the humps over time in RZ

Leo. In addition to the double-humps, the systems SDSS J080434.20+510349.2 and SDSS J123813.63-033933.0 share the common characteristic with RZ Leo of small brightenings (Aviles et al. 2010), although the former systems are thought to contain brown dwarfs while RZ Leo has a longer period and appears to have a normal main sequence secondary (Mennickent et al. 1999).

The DFT for RZ Leo also shows significant high amplitude signals at 220 s and its harmonic of 110s, with the amplitude of the harmonic (40 millimodulation amplitude; mma) being slightly larger than the 220 s (32 mma). Lower amplitude periods of 206s and 106s also appear close to these periods. The beat period of the close periods of 220s and 206s would be 41.7 min, which does not correspond to any observed period. The long duration (80 days) of the short cadence K2 optical data in 2014 is ideal for searching for small amplitude periodic signals. The result reveals a period at 220.65s with an amplitude of about 6 mma, along with linear combination periods (196s) with the orbital period of RZ Leo and harmonics (Figure 2). The one minute cadence of K2 was too long to pick up the presence of the 110s harmonic, or the close 206 and 106s periods. Unfortunately, these periods of 220 and 196s are known artifacts in short cadence K2 data (the 8th and 9th harmonics of the long cadence 29.42 min sampling of K2, see Gilliland et al. 2010). Thus, the K2 data cannot confirm the optical presence of the periods seen in the UV observation. Possible interpretations of the UV periods include white dwarf pulsation or spin. Accreting white dwarf pulsators generally do not show harmonics of the pulse in the UV and the pulsations wander slightly in frequency over time (Szkody et al. 2010). The spin periods of white dwarfs are very stable over time and usually show up in X-ray observations. A few IPs (e.g. CC Scl, V455 And) show both the spin and the harmonic of the spin period, with the harmonic stronger than the rotation period at times (Woudt et al. 2012, Mukadam et al. 2016). Reis et al. (2013) reported *Swift* – *XRT* data and modeling of RZ Leo, determining a 0.5-10 keV luminosity of  $7.4 \pm 0.4 \times 10^{29}$  erg s<sup>-1</sup>, (10 times the luminosity of

V455 And). This is on the low end, but within the range, of IPs. The observation was too short (3798 s) to determine short timescale periods. The UV presence and strength of this period of 220 s and its harmonic, implies that this is the spin period of the white dwarf and RZ Leo is likely an IP, but longer X-ray and optical observations will be needed to confirm this identification.

The single night (4 hrs) of APO data (Figure 3) does not show the 220 s period. While the noise level in the DFT is much larger than the K2 data due to the short length of the dataset, the increased aperture and time resolution results in a  $3\sigma$  noise level of 6.5 mma. However, the 2016 APO light curve looks different than the 2014 K2 one, in that the double humps are of similar amplitude, whereas the typical RZ Leo light curve has one hump with about half the amplitude of the other. It is possible that different accretion levels may affect the ability to detect the spin in the optical.

The short exposures of the APO data (20 s), compared to the 1 min cadence of K2 and the 4-5 min exposures of Patterson et al. (2003) and Mennickent et al. (1999), reveal possible eclipse-like features near times of 4800 s and 11,400 s (in Figure 3), which correspond to the orbital period. The short duration of this feature (about 3 min) could account for why it was not evident in previous reported data. Phasing and folding our data with the ephemeris in Dai et al. (2016), based on the maximum of the primary orbital hump, shows the repeatability of the eclipse shape (Figure 4). However, further photometry with short exposures and over several days will be needed to confirm if this is indeed a partial eclipse and if the spin period can be detected in the optical.

### 3.2. CC Scl

In contrast to RZ Leo, the UV light curve of CC Scl (Figure 5 top) is completely dominated by the spin modulation of the white dwarf and its harmonic that Woudt et al. (2012) only saw during the 2011 November outburst. The DFT (Figure 5 bottom) shows the harmonic of the spin at 194.6 s with a much higher amplitude (220 mma) than the spin period of 389 s (90 mma). Our UV data show that the spin modulation is clearly present at quiescence. Since the Woudt et al. (2012) observations were accomplished using the *Swift* UVOT with a filter centered at 2246 Å, it is possible that the variability at longer UV wavelengths has lower amplitude due to a high temperature of the accreting areas. Pala et al. (2017) determined a white dwarf temperature of  $16,855 \pm 801$  K for CC Scl from the average spectrum, but note that the white dwarf only contributes about 35% of the total UV flux (using a power law or constant flux addition for the remainder) and so the temperature is not very reliable. At outburst, the X-ray and UVOT data of Woudt et al. (2012) show only the primary spin period and not the harmonic (although the optical shows the harmonic at varying amplitudes). As the outburst faded over 8 days, the amplitude of the spin modulation decreased until it was invisible at 9 days past outburst peak. This led Woudt et al. (2012) to postulate that the higher accretion rate at outburst resulted in the disk blocking the second pole, while at quiescence both poles are seen but the second pole is anti-phased with the primary so the modulation is cancelled out. Our *HST* observation disproves this idea and indicates that both poles contribute to the spin modulation without cancellation. The optical data taken for CC Scl around the time of our *HST* observation (Pala et al. 2017) show a small outburst (magnitude 15.3 versus the usual 13.4, and duration only 5 days) on 2013 June 13, 16 days prior to the *HST* data, and a return to quiescence on June 16. While it is possible that this event triggered a longer visibility of the spin modulation, we consider this unlikely due to the smaller, shorter outburst in 2013 versus 2011, and the longer period in quiescence preceding our observation.



In order to estimate the temperature of the accretion areas, we applied a procedure similar to that used to study the temperature variations in the dwarf nova GW Lib (Toloza et al. 2016). This involved using the Markov chain Monte Carlo (MCMC) ensemble sampler to fit two spectra, one obtained from the peaks of the lightcurve and a second obtained from the troughs. The count rates used to create the peak and trough spectra for CC Scl are shown by the lines in Figure 6 and the resulting two spectra are shown in Figure 7. Besides the flux difference, the broader  $\text{Ly}\alpha$  absorption line and the flatter shape of the trough spectrum are indicative of a temperature decrease.

We employed a grid of white dwarfs models (Hubeny & Lanz 1995) covering a temperature range of 9000-30000 K in steps of 100 K with the metallicity set to 0.2 times the solar abundance and with  $\log g=8.35$  (Pala et al. 2017), corresponding to the average mass of white dwarfs in CVs (Zorotovic et al. 2011). The airglow emission lines of  $\text{Ly}\alpha$  and O I were masked out in the range of 1207.20-1225.26 Å and 1295.30-1312.44 Å, respectively. The emission lines of C III1176, C III1335, Si IV1400, and C IV1400 were fitted with gaussians.

The core of the  $\text{Ly}\alpha$  absorption reveals evidence for a second component. This second component has been identified in many dwarf novae (Godon et al. 2004, Long et al. 2009, Sion et al. 2003, Gänsicke et al. 2005), although its nature and origin remain unclear. In dwarf novae, this component is likely related to the disk and/or boundary layer emission. For IPs, the situation is further complicated by additional contributions to the UV light from the accretion curtains, and the heated white dwarf areas at the magnetic poles. The UV observations of many polars show large variations of the white dwarf temperature during their orbits as large areas near their magnetic poles that are heated by irradiation from the accretion columns come into view. This has been studied in most detail in the prototype AM Her (Gänsicke et al. 1995, 1998, 2006; König et al. 2006), but is a general feature of this class of strongly magnetic CVs (Stockman et al. 1994, Schwöpe et al. 2002).

Even the treatment of this heated spot area is problematic as a realistic model needs to encompass a temperature change from the center of the spot to the unheated white dwarf (Gänsicke et al. 2006) as well as non-circular spots (Linnell et al. 2010). Due to the limited wavelength and orbital coverage of our data, we merely approximated the second component as a power law (with its contribution to the peak and trough spectra determined by the core flux of  $\text{Ly}\alpha$ ) and then tried to fit the two spectra, first trying a single white dwarf, and then a dual temperature white dwarf with one temperature fixed to the trough white dwarf temperature. Even these simple models involve 4 free parameters for the single white dwarf (the white dwarf temperature, scaling factor, power law constant and exponent) while the dual temperature white dwarf invokes an additional parameter.

The shape of the light curve of CC Scl imitates a sinusoidal-like pattern, suggesting that the hot areas are not fully self-eclipsed, thus preventing a reliable estimate of the underlying unheated white dwarf temperature. Fitting the trough spectrum of CC Scl with a single white dwarf model along with a power law, we obtain an upper limit to the white dwarf temperature of  $15,612^{+139}_{-129}$  K, which is likely an average of a lower temperature white dwarf and some warmer heated area on the white dwarf. This fit is shown in Figure 7 and involves a power law that contributes 65% of the observed flux along with this average temperature white dwarf. If we invoke the same fitting for the peak spectrum, we obtain a white dwarf of  $18,751 \pm 164$  K, with a power law contributing 60% (fit shown to peak flux in Figure 7).

Since the accretion areas likely have a steep temperature gradient near the infalling material, we also tried to model the peak spectrum using the average white dwarf temperature found from the trough spectrum (15,612 K) plus a hotter spot area that is viewed during the peak phases, plus a power law. This resulted in a fit with the hotter spot temperature of  $24,170^{+848}_{-586}$  K and an area covering less than 9.5% of the visible surface of

the white dwarf, with the power law component contributing 42%. In this fit, the average flux of the cool white dwarf plus its warm area had to increase by a factor of 1.5 implying an increase of its warm spot area as well. Since we cannot disentangle the warm spot area from the rest of the white dwarf and the total flux is dominated by the component modelled as a power law, the temperatures are not well constrained. We can conclude that the temperature of the area viewed during UV peak phases is several thousand degrees hotter than that at the trough phases.

An analysis of the UV spectrum of several other IPs (AE Aqr, FO Aqr, EX Hya, PQ Gem) has been accomplished using the Faint Object Spectrograph (Eracleous et al. 1994, de Martino et al. 1998,1999; Stavroyiannopoulos et al. 1997) and the Space Telescope Imaging Spectrograph (Belle et al. 2003). Almost all of these studies showed two or more components giving rise to the UV flux. One of the components was always part of a white dwarf, with temperature of 23,000 K (Belle et al. 2003) for EX Hya, 26,000 K for AE Aqr (Eracleous et al. 1994), 30,000 K for PQ Gem (Stavroyiannopoulos et al. 1997) and 36,000 K for FO Aqr (de Martino et al. 1999). The second component was a much larger black body or disk or column that was much cooler ( $T < 12,000$  K). The temperatures derived for the white dwarf in CC Scl are lower than in these three systems. This is consistent with the short orbital period of CC Scl, its low magnetic moment (Woudt et al. 2012), and its low mass ratio suggestive of a post-period minimum system (Longa-Pena et al. 2015). The average white dwarf temperature in CC Scl measured from the UV faint phases (trough) of 15,612 K, is similar to the values obtained for the short-period polars V834 Cen, BL Hyi and MR Ser (Araujo-Betancor et al. 2005b), indicating a similar accretion rate (Townesley & Gänsicke 2009). The power laws, which increase toward shorter wavelengths, are in good agreement with the presence of a magnetic or other hot component.

#### 4. Conclusions

The UV light curves obtained from time-tag COS spectral data reveal several new facets of RZ Leo and CC Scl. The UV light curve of RZ Leo in 2013 shows periods of 220 s and its harmonic at 110 s, thus making it a likely new member of the small class of IPs with orbital periods less than 2 hrs. Two years later, optical ground-based photometry obtained over a 4 hr timescale does not show this signal, but does indicate a possible partial eclipse. Further X-ray and optical data are needed to confirm this classification. CC Scl at quiescence shows very prominent UV visibility of the spin period previously observed only at outburst, with the harmonic having a larger amplitude than the spin period itself. This indicates both accretion poles contribute to the modulation at quiescence. Fitting white dwarf plus power law models to the spectra created from the peaks versus troughs of the spin count rates show increases in temperature of several thousand degrees when the accretion poles are in view. However, since the power law component is a significant part of the observed UV flux, a better understanding of the temperature gradient and contribution of each of the magnetic heated poles, along with a distance determination, is needed to further constrain the temperatures and areas involved.

In the Mukai catalog, only about 10% of the IPs have orbital periods below 2 hours, like RZ Leo and CC Scl. Since both theoretical and observational arguments have been made (e.g. Lasota et al. 1995) for the presence of truncated disks in low accretion rate short orbital period systems, it is possible that the number of IPs in this period range is much larger. However, as this paper demonstrates, it is difficult to detect spin periods in these systems.

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Table 1. Summary of HST COS Observations

Object	UT Date	$\lambda$ (Å)	UT Time Range	Exp (s)
RZ Leo	2013 April 11	1122-1980	08:35:43-14:08:15	10504.736
CC Scl	2013 June 29	1121-1960	03:39:03-05:46:30	4667.776

## RZ Leo (11 April 2013 UT)

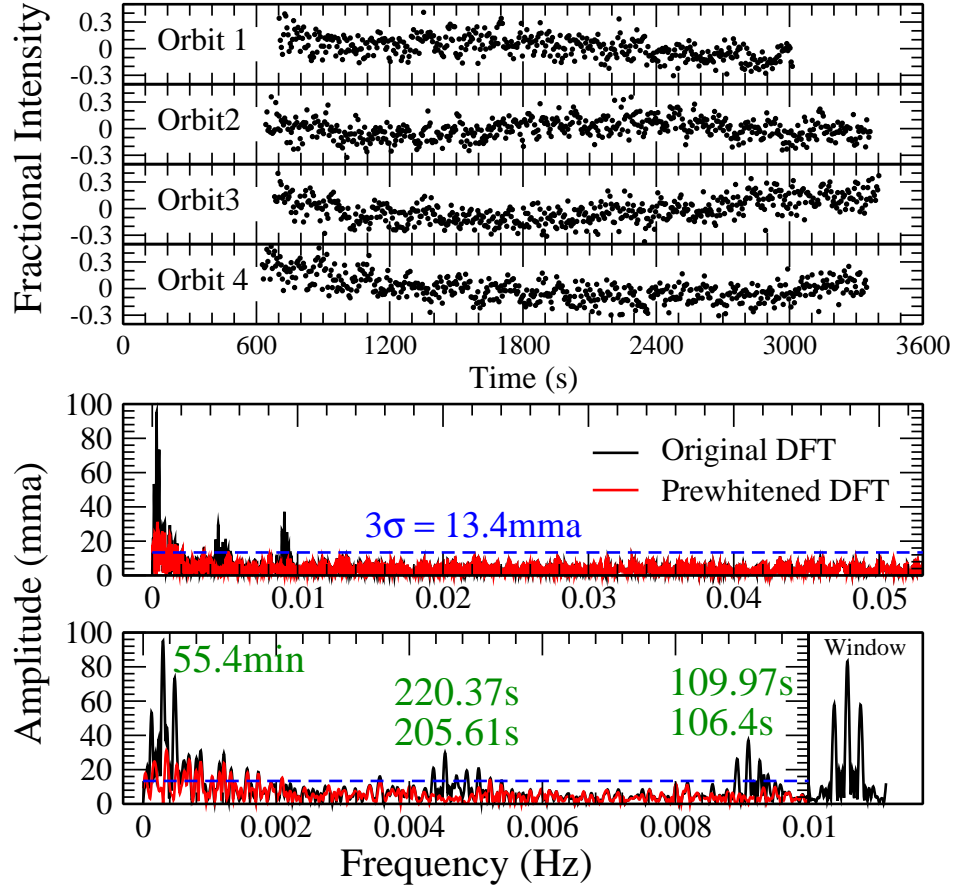


Fig. 1.— Fractional intensity light curve (top), total DFT (mid) and expanded DFT at low frequencies (bottom) of the 4 orbits of COS time-tag data on RZ Leo obtained on 2013 April 11.

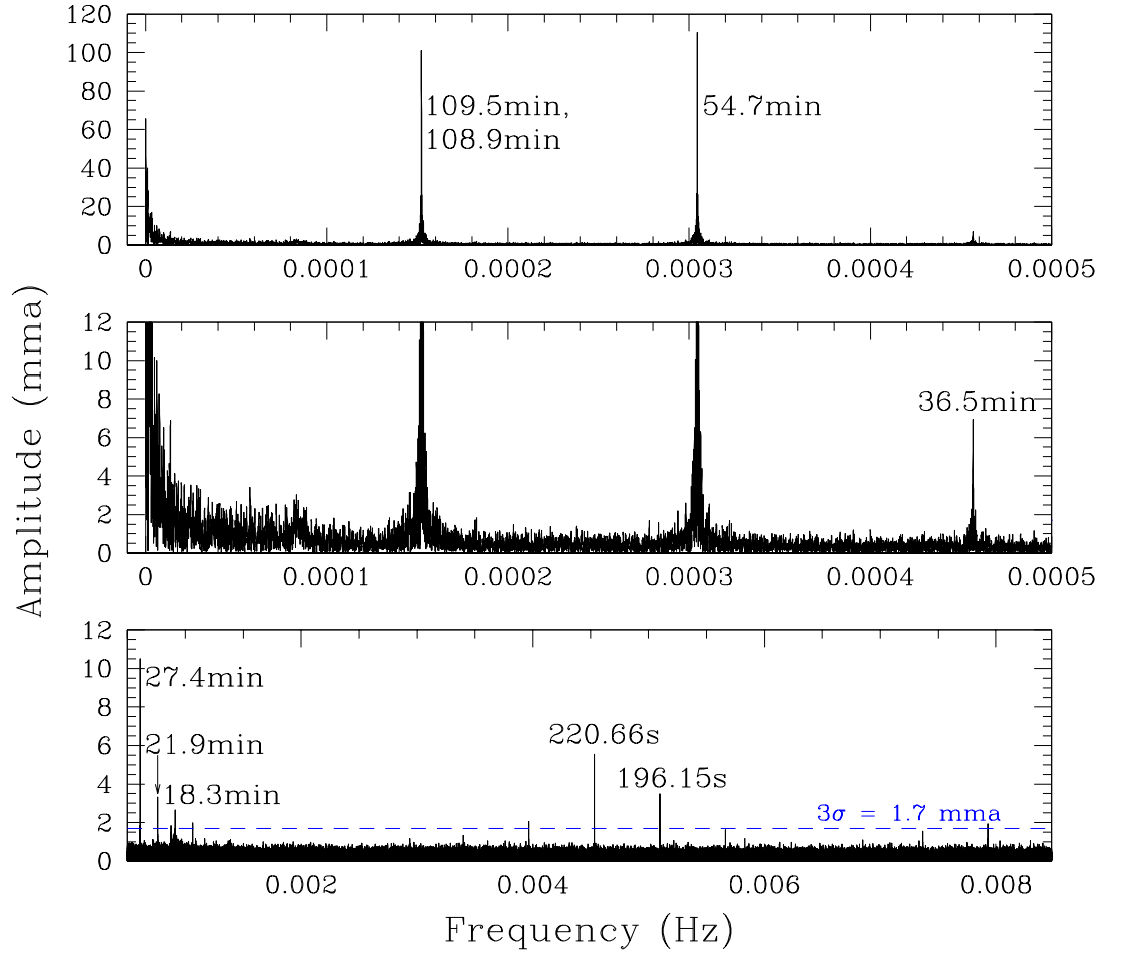


Fig. 2.— DFT of short cadence K2 continuous light curve data on RZ Leo from 2014 May 30 through Aug 20. Middle panel shows the same frequency range as the top panel but expands the low amplitudes. Bottom panel plots the entire frequency range to the Nyquist frequency (120 s). The peak labelled 109.5 is the orbital period, with harmonics at 54.7, 36.5, 27.4, 21.9 and 18.3 min, 220 s and 196 s are the 8th and 9th harmonics of the K2 long cadence sampling time. The blue line shows the  $3\sigma$  level determined from the shuffling technique described in Szkody et al. (2012).

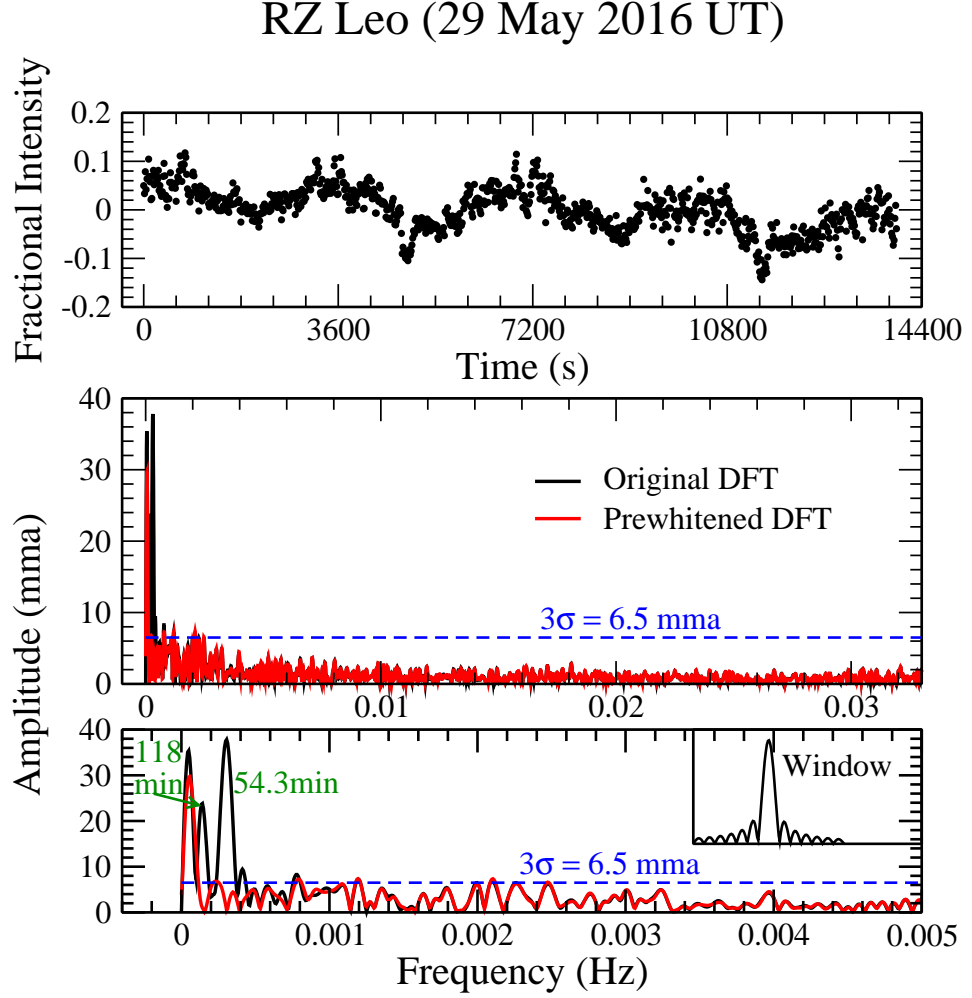


Fig. 3.— Fractional intensity light curve and DFT of RZ Leo obtained at APO on 29 May 2016 with 15 s integration times.

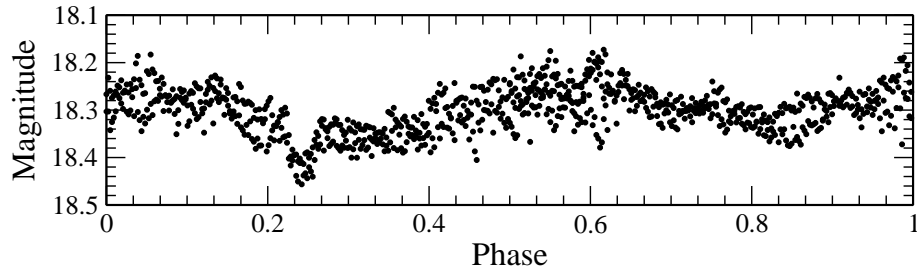


Fig. 4.— RZ Leo APO data converted to approximate  $g$  magnitudes using comparison stars from SDSS and phased on the ephemeris given in Dai et al. (2016), where phase 0 is the maximum of the primary orbital hump. Each point has an error bar of about 0.01 mag.

# CC Scl (29 June 2013 UT)

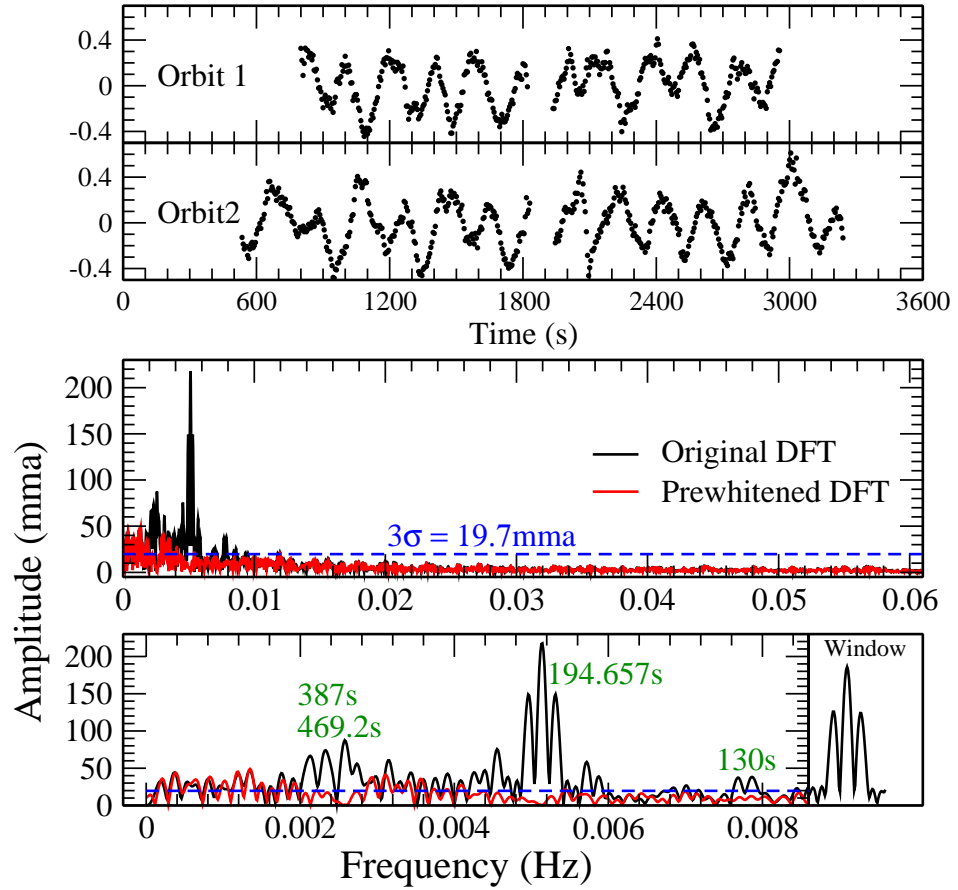


Fig. 5.— Fractional intensity light curve and DFT of the 2 orbits of COS time-tag data on CC Scl obtained on 2013 June 29.

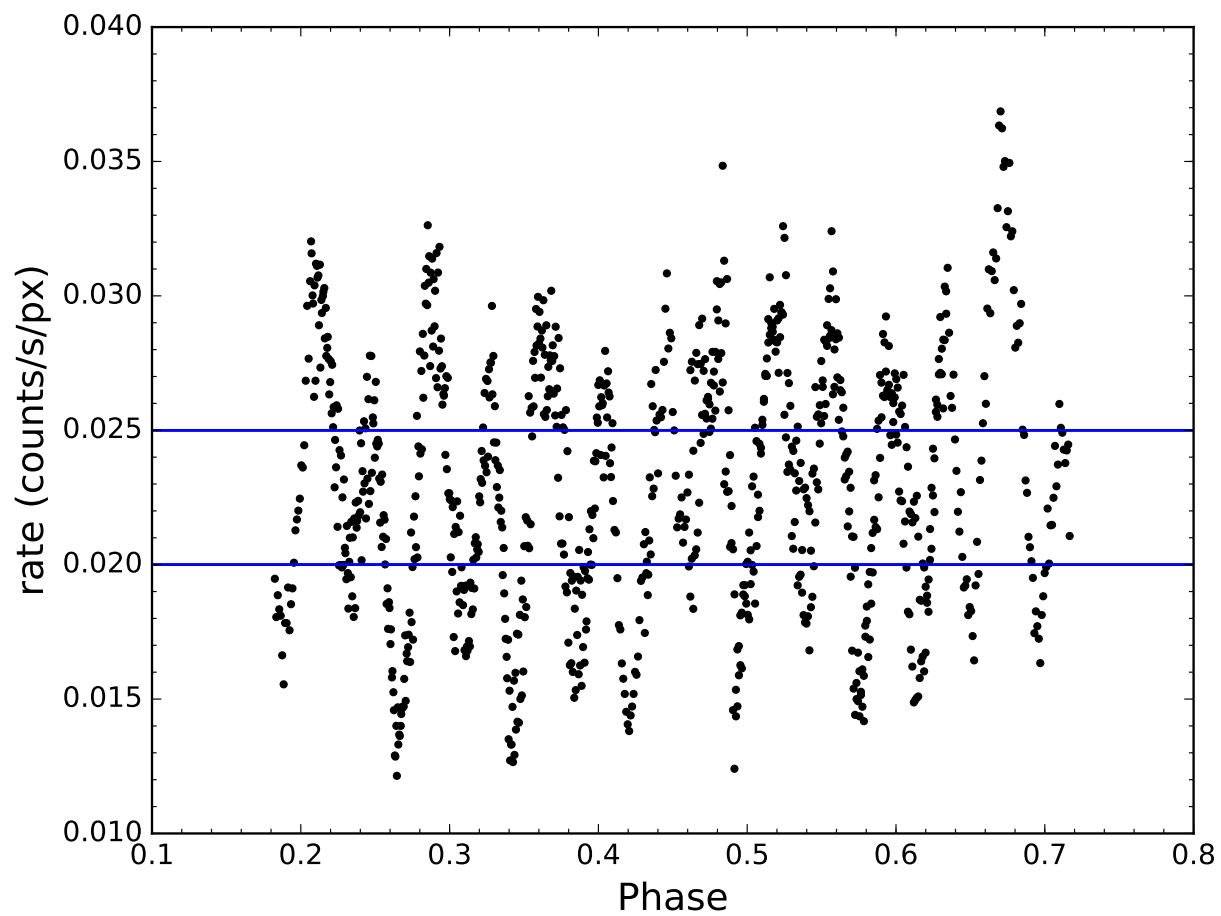


Fig. 6.— HST Count rate light curve of CC Scl showing the regions used to create the peak spectrum (above the top line) and the trough spectrum (below the bottom line).

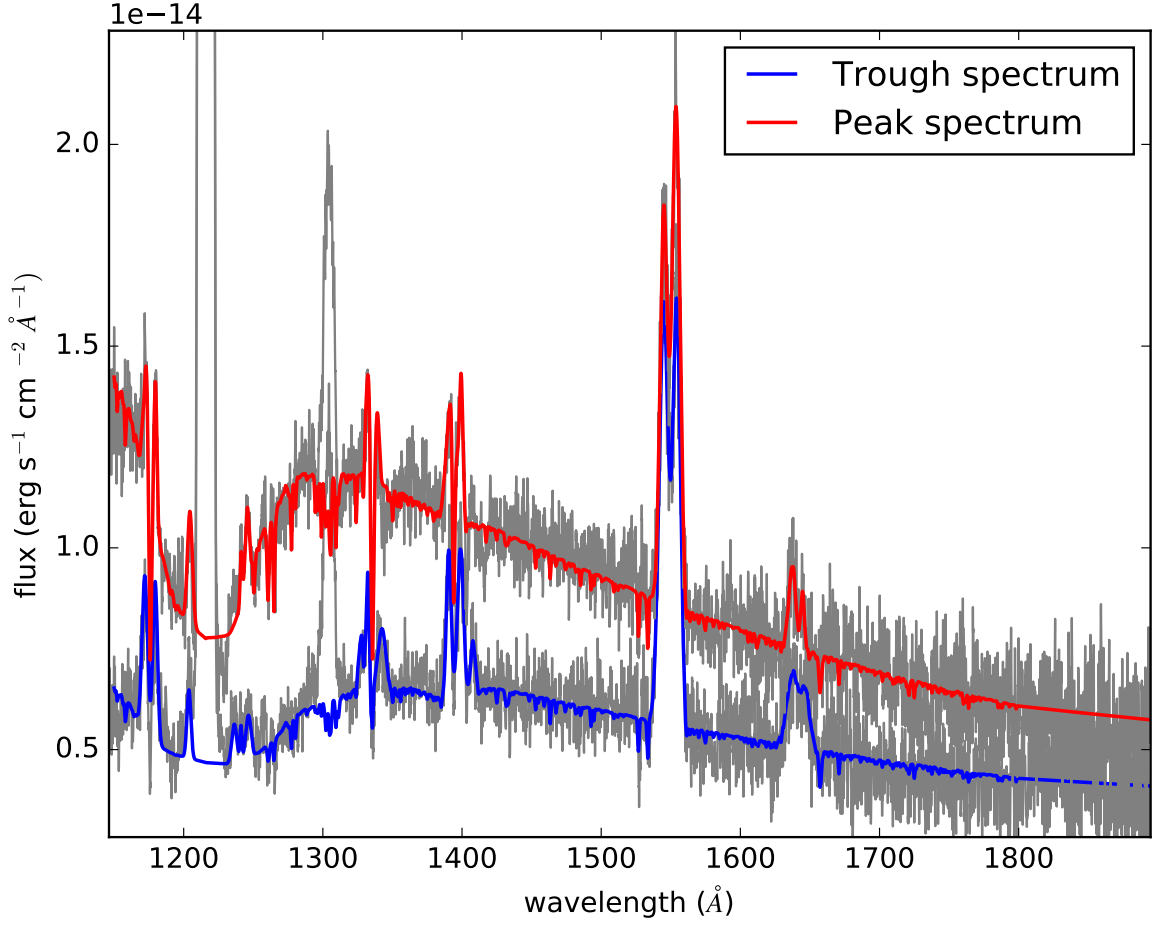


Fig. 7.— The CC Scl spectra created from the peaks (top grey), and troughs (bottom grey) of the data shown in Figure 6, along with a model white dwarf and power law fit. The trough spectral fit (blue) is for a 15,612 K white dwarf along with a power law contributing 65%, while the peak fit uses an 18,751 K white dwarf (red) along with a power law contributing 60%.